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(54) **SEMICONDUCTOR DEVICE HAVING LOCALIZED CHARGE BALANCE STRUCTURE AND METHOD**

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H01L 29/06	(2006.01)
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CPC H01L 29/7801; H01L 29/7802; H01L 29/781; H01L 29/7813; H01L 29/7811

USPC 257/330, 332, E29.027; 438/270

See application file for complete search history.

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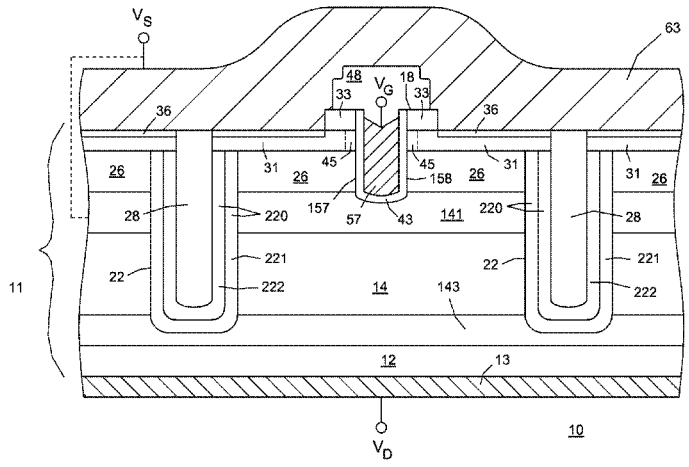
(57) **ABSTRACT**

In one embodiment, a semiconductor device has a superjunction structure formed adjoining a low-doped n-type region. A low-doped p-type region is formed adjoining the superjunction structure above the low-doped n-type region and is configured to improve Eas characteristics. A body region is formed adjacent the low-doped p-type region and a control electrode structure is formed adjacent the body region for controlling a channel region within the body region.

20 Claims, 5 Drawing Sheets



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H01L 29/10 (2006.01)

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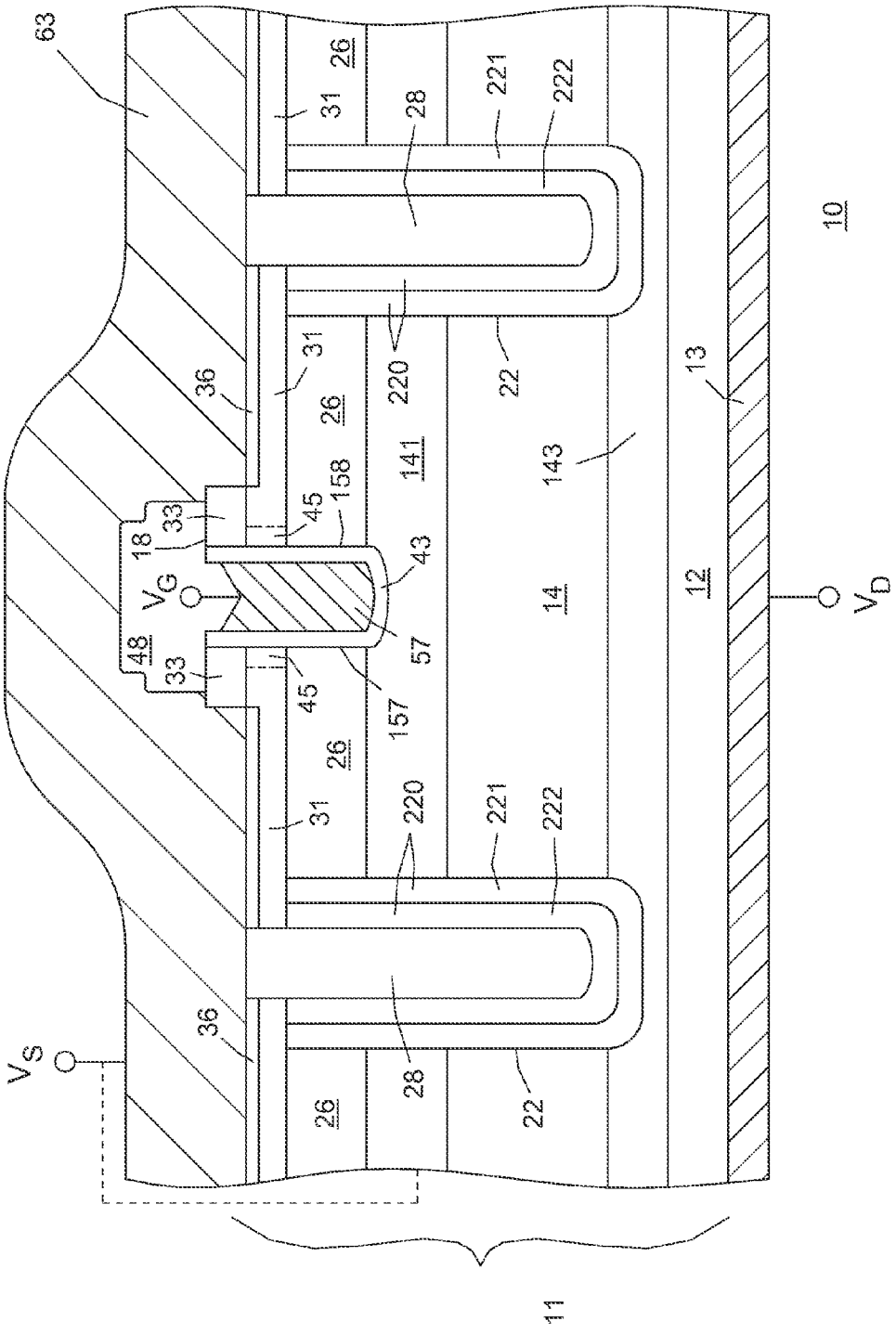
63
26
31
28
221
222
10
36
31
220
22
13
26
141
143
158
45
33
18
43
V_G
14
12
V_D
48
33
45
57
157
26
31
220
221
222
36
V_S
28
26
22
11

FIG. 1

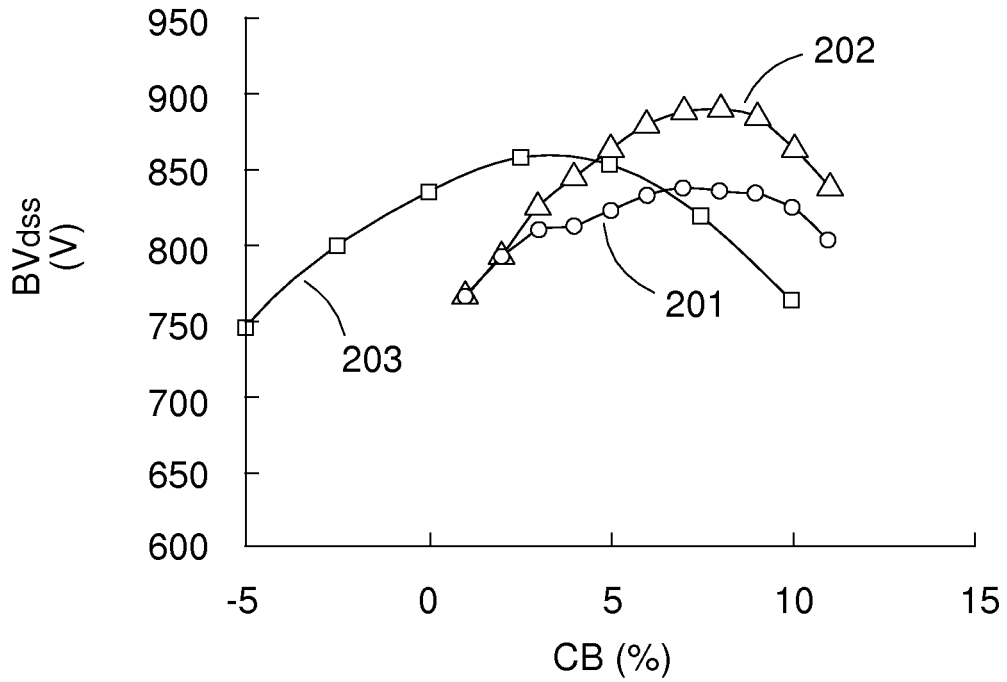
950
900
850
800
750
700
650
600
BVdss (V)
-5
0
5
10
15
CB (%)
202
201
203

FIG. 2

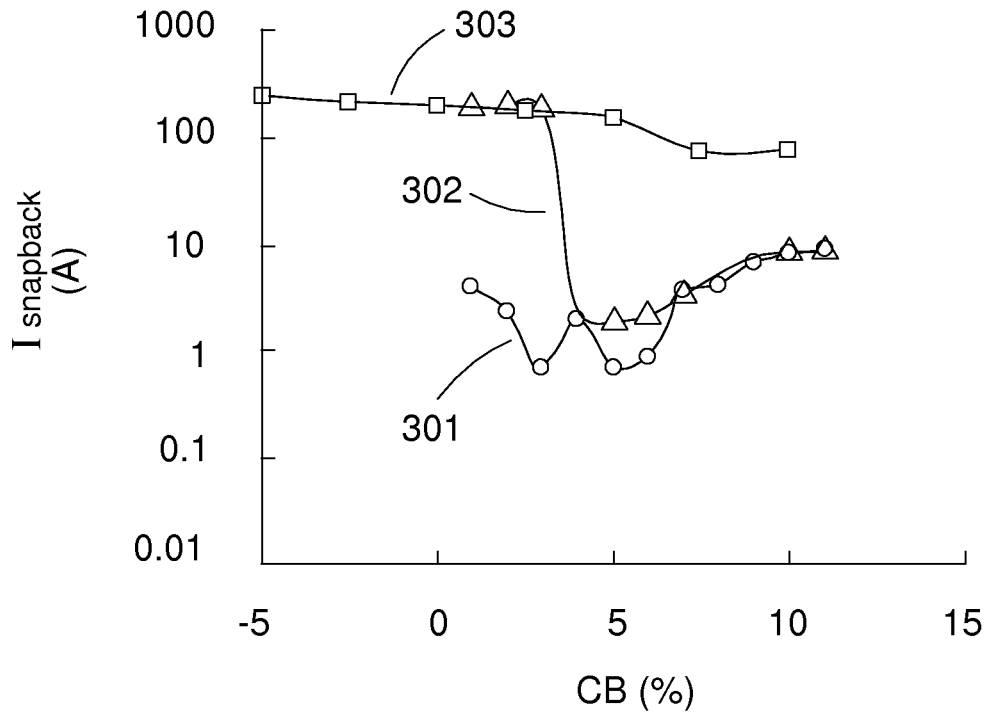
1000
100
10
1
0.1
0.01
I snapback (A)
-5
0
5
10
15
CB (%)
303
302
301

FIG. 3

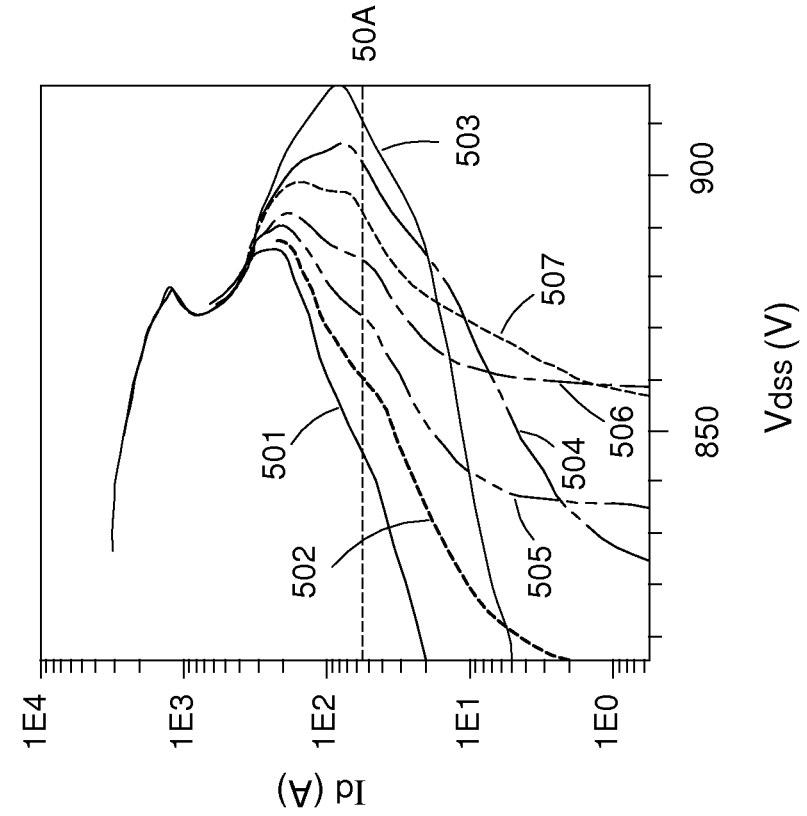
50A
503
507
501
506
504
502
505
1E4
1E3
1E2
1E1
1E0
Id (A)
900
850
Vdss (V)

FIG. 5

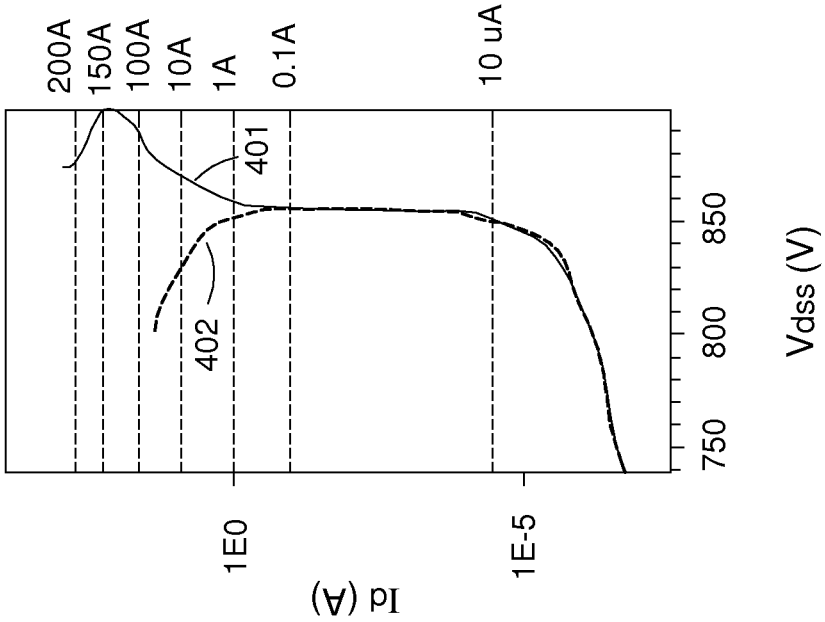
200A
150A
100A
10A
1A
0.1A
10 uA
401
402
1E0
1E-5
Id (A)
850
800
750
Vdss (V)

FIG. 4

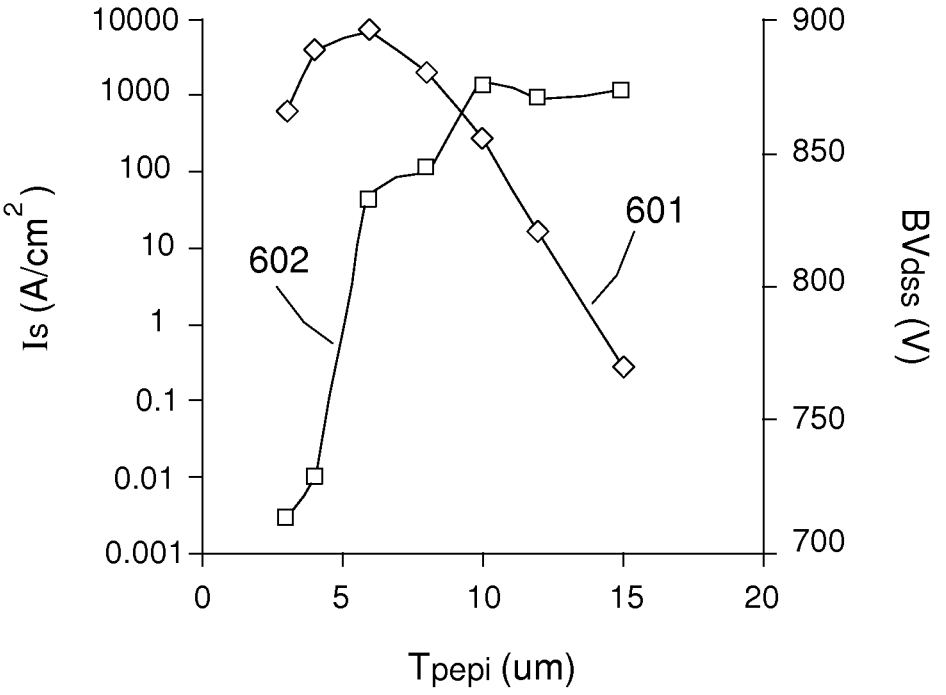
10000
1000
100
10
1
0.1
0.01
0.001
Is (A/cm2)
900
850
800
750
700
BVdss (V)
0
5
10
15
20
Tpepi (um)
601
602

FIG.6

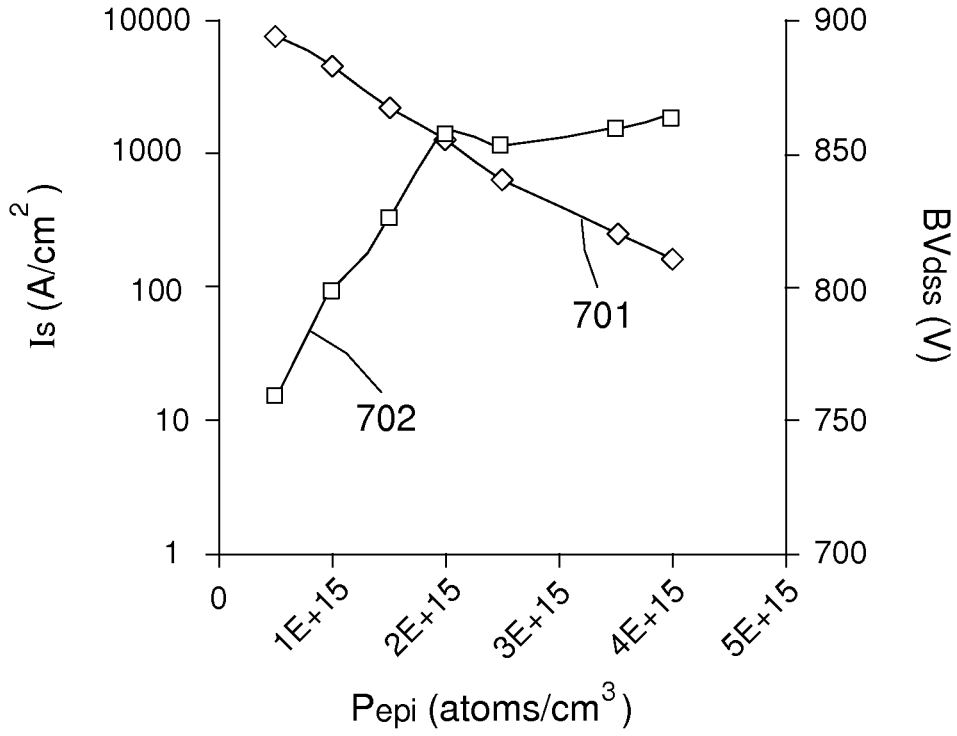
10000
1000
100
10
1
Is (A/cm2)
900
850
800
750
700
BVdss (V)
0
1E+15
2E+15
3E+15
4E+15
5E+15
Pepi (atoms/cm3)
701
702

FIG. 7

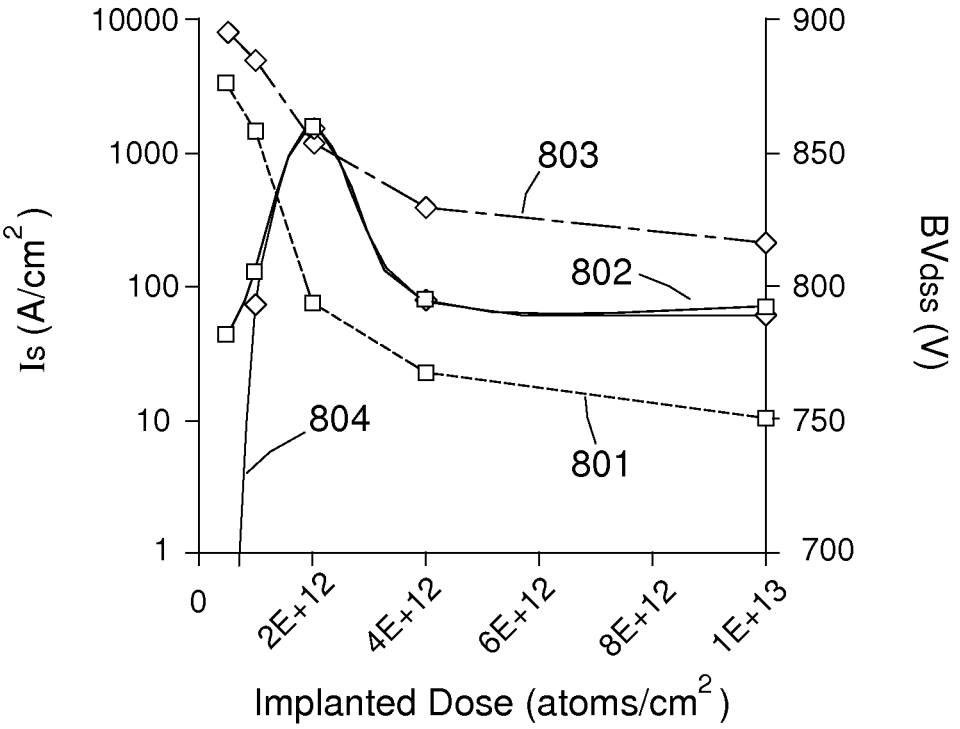
10000
1000
100
10
1
Is (A/cm^2)
900
850
800
750
700
BVdss (V)
803
802
804
801
0
2E+12
4E+12
6E+12
8E+12
1E+13
Implanted Dose (atoms/cm^2)

FIG. 8

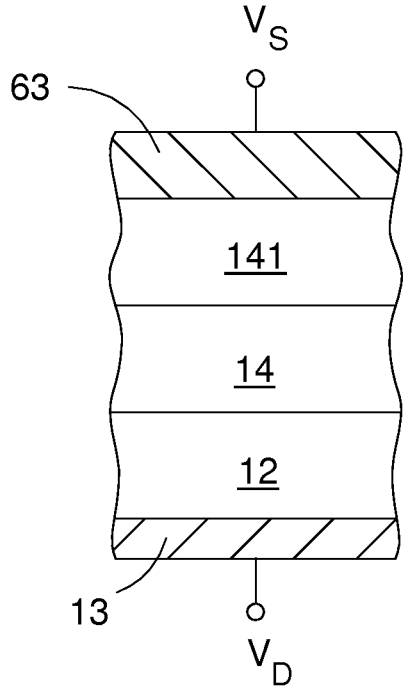
V_S
63
141
14
12
13
V_D

FIG. 9

SEMICONDUCTOR DEVICE HAVING LOCALIZED CHARGE BALANCE STRUCTURE AND METHOD

CROSS REFERENCE TO RELATED APPLICATION

This application claims the benefit of priority from U.S. Provisional Application No. 61/710,460, which was filed on Oct. 5, 2012 and fully incorporated herein.

BACKGROUND

The present invention relates, in general, to electronics and, more particularly, to methods of forming semiconductors and structures therefore.

Metal-oxide semiconductor field effect transistors (MOSFETs) are a common type of power switching device. A MOSFET device includes a source region, a drain region, a channel region extending between the source and drain regions, and a gate structure provided adjacent to the channel region. The gate structure includes a conductive gate electrode layer disposed adjacent to and separated from the channel region by a thin dielectric layer.

When a MOSFET device is in the on state, a voltage is applied to the gate structure to form a conduction channel region between the source and drain regions, which allows current to flow through the device. In the off state, any voltage applied to the gate structure is sufficiently low so that a conduction channel does not form, and thus current flow does not occur. During the off state, the device must support a high voltage between the source region and the drain region.

Today's higher voltage power switch market is driven by at least two major parameters, which include breakdown voltage (BVdss) and on-state resistance (Rdson). For a specific application, a minimum breakdown voltage is required, and in practice, designers typically can meet a BVdss specification. However, this is often at the expense of Rdson. This trade-off in performance is a major design challenge for manufacturers and users of high voltage power switching devices.

Recently, superjunction devices have gained in popularity to improve the trade-off between Rdson and BVdss. In previous n-channel superjunction devices, multiple heavily-doped diffused n-type and p-type regions replace one lightly doped n-type epitaxial region. In the on state, current flows through the heavily doped n-type regions, which lowers Rdson. In the off or blocking state, the heavily doped n-type and p-type regions deplete into or compensate each other to provide a high BVdss. Although superjunction devices look promising, significant challenges still exist in manufacturing them.

Another problem with previous superjunction devices is that the energy capability (Eas) under unclamped inductive switching (UIS) testing is often too low under optimum charge balance (for example, CB approaching 0%) or within a desired charge balance window. Such inadequate Eas capability is believed to be from low snapback current (Isnapback) in the reverse blocking IdVd curve. A low Isnapback can produce a pure electrical failure observed at few nanoseconds after switching-off the device in the typical UIS test. The electrical failure can occur when a negative differential resistance is reached at a certain region of the active area, thus producing a non-uniform current distribution and, eventually, a current focalization or a "hot spot". Additionally, a low Isnapback can limit the energy capability under other tests, such as reverse recovery tests.

Accordingly, it is desirable to have a structure for and method of making a charge balanced semiconductor device that improves Eas performance for an optimum charge balance and/or a selected charge balance window. It would be beneficial if the structure and method maintained the design trade-offs between Eas, Rdson, and BVdss. Additionally, it would beneficial if the structure and method did not add significant process complexity or excessive costs.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates a cross-sectional view of an embodiment of a semiconductor device in accordance with the present invention;

FIG. **2** illustrates graphical information of breakdown voltage (BVdss) vs. charge balance (CB) comparing an embodiment of the present invention to previous structures;

FIG. **3** illustrates graphical information of snapback current (Isnapback) vs. CB comparing an embodiment of the present invention with previous structures;

FIG. **4** illustrates graphical information of reverse mode drain current (Id) and drain-to-source voltage (Vdss) curves extracted at CB=5% comparing an embodiment of the present invention to a prior structure;

FIG. **5** illustrates graphical information of reverse mode IdVdss curves extracted at different CB levels in a structure in accordance with the present invention;

FIG. **6** illustrates graphical information of Isnapback and BVdss versus thickness of a structure in accordance with an embodiment of the present invention;

FIG. **7** illustrates graphical information of Isnapback and BVdss versus dopant concentration of a structure in accordance with an embodiment of the present invention;

FIG. **8** illustrates graphical information of Isnapback and BVdss versus ion-implant dose and dose location in accordance in accordance with another embodiment of the present invention; and

FIG. **9** illustrates a partial cross-sectional view of a further embodiment of a structure in accordance with the present invention.

For simplicity and clarity of the illustration, elements in the figures are not necessarily drawn to scale, and the same reference numbers in different figures denote the same elements. Additionally, descriptions and details of well-known steps and elements are omitted for simplicity of the description. For clarity of the drawings, certain regions of device structures, such as doped regions or dielectric regions, may be illustrated as having generally straight line edges and precise angular corners. However, those skilled in the art understand that, due to the diffusion and activation of dopants or formation of layers, the edges of such regions generally may not be straight lines and that the corners may not be precise angles. Furthermore, the term "major surface" when used in conjunction with a semiconductor region, wafer, or substrate means the surface of the semiconductor region, wafer, or substrate that forms an interface with another material, such as a dielectric, an insulator, a conductor, or a polycrystalline semiconductor. The major surface can have a topography that changes in the x, y and z directions.

DETAILED DESCRIPTION OF THE DRAWINGS

In accordance with the present description, a local charge balance (LCB) structure is disclosed to overcome, among other things, the Eas problems with previous semiconductor devices. The present embodiment is compatible with current semiconductor device processing methods. In the present

embodiment, a thick and low doped p-type region can be formed below an n-type linking region and above the n-type drift region of the LCB device. Advantages of the present embodiments include, but are not limited to, suppression of the Is/Eas well, reduced or no avalanche in the vicinity of the gate trench (which adds to repetitive avalanche ruggedness), and increased breakdown voltage (BVdss) in n-type rich designs. By way of example, the low doped p-type region can be formed using techniques such as epitaxial growth, ion implantation, or other doping techniques as known to those of ordinary skill in the art. The present embodiment is described as an n-channel structure; however, those skilled in the art will appreciate that the present description is suitable for p-channel structures by changing the noted conductivity types from n-type to p-type and vice versa.

Some previous global charge balance (GCB) structures have exhibited unacceptable Eas when the charge balance is less than zero percent (CB<0%). This is explained, at least in part, by considering that when CB<0%, the parasitic bipolar can be more susceptible to being activated. In some devices, the low Eas values have exhibited negligible improvement by increasing the p-type body region and the p+ contact ion implant doses during processing. As a consequence, it is believed that the activation of the parasitic bipolar transistor in GCB structures plays a secondary role in the failure at low Eas.

In addition, certain previous LCB structures have exhibited unacceptably low Eas when CB tends to 0%. This Eas characteristic exhibits a U-shaped curve with the lowest point on the curve located proximate to CB=0%. Note also that CB=0% is generally defined as the point where BVdss approaches a maximum value, which can differ from the CB defined in any given process. It has also been found that there is a correlation between a measured low Eas and simulated Isnapback. A low Isnapback characteristic at CB=0% is believed to be due to the rapid increase of charge density when the LCB device goes into avalanche, which results in negative differential resistance. It has been observed that when CB<0% and CB>0%, a non-rectangular distribution of the electric field in the drift region is believed to avoid such a rapid increase of the charge density. In a conventional GCB structure, a similar Isnapback trend and characteristic has been observed by simulation.

There is a need to elevate the Isnapback level in both GCB and LCB structures. One previous technique used in an attempt to elevate the Isnapback level in planar devices has been to add an n-type buffer layer between the drift region and the n+-substrate. The n-type buffer layer has been shown to increase Eas for CB=0%. In addition, simulations have reproduced similar results by showing an improved Isnapback when the electric field penetrates into the n-type buffer layer. Although the Eas can be boosted about one order of magnitude, the Eas vs. CB curve still suffers an undesirable U-shape effect noted previously. Moreover, Rdson can undesirably increase by 20% with the n-type buffer layer due to the additional series resistance at the end of the drift region, which is undesirable.

FIG. **1** shows a partial cross-sectional view of an insulated gate field effect transistor (IGFET), MOSFET, LCB superjunction device, superjunction structure, charged-compensated, LCB structure, or switching device or cell **10** in accordance with a first embodiment that is configured to address the issues with prior devices described previously. By way of example, device **10** is among many such devices integrated with logic and/or other components into a semiconductor chip as part of a power integrated circuit. Alternatively, device **10** is among many such devices integrated together to form a discrete transistor device.

Device **10** includes a region of semiconductor material **11**, which comprises, for example, an n-type silicon substrate **12** having a resistivity in a range of approximately 0.001 to about 0.01 ohm-cm, and may be doped with arsenic or phosphorous. In the embodiment shown, substrate **12** provides a drain region for device **10**, which is adjacent to a conductive layer **13**. A semiconductor layer **14** is formed in, on, or overlying substrate **12** and is n-type and doped light enough in one embodiment so as to not impact charge balance in the trench compensation regions described below. In one embodiment, layer **14** is formed using epitaxial growth techniques. In an embodiment suitable for a 650 volt device, layer **14** is doped n-type with a dopant concentration of about 1.0×10^{13} atoms/cm^3 to about 50×10^{14} atoms/cm^3, and has a thickness on the order of about 40 microns to about 70 microns. Note that although semiconductor layer **14** is shown as thicker than substrate **12** in the drawings, substrate **12** actually can be thicker. It is shown this way for ease of understanding in the drawings. The thickness of layer **14** is increased or decreased depending on the desired BVdss rating of device **10**. Additionally, those skilled in the art will understand that an insulated gate bipolar transistor (IGBT) device is achieved with the present structure by, for example, changing the conductivity type of substrate **12** to p-type (i.e., opposite to semiconductor layer **14**).

In accordance with the present embodiment, device **10** further includes a semiconductor layer **141** (also referred to a "p-type layer" or a "buried p-type layer" when device **10** is an n-channel device) formed in or within a portion of semiconductor layer **14**. As illustrated in FIG. **1**, semiconductor layer **141** is spaced apart or separated from major surface by other or intervening regions in the finished device **10**. In one embodiment, semiconductor layer **141** is doped p-type with a dopant concentration of about 1.0×10^{15} atoms/cm^3 to about 4.0×10^{15} atoms/cm^3. In another embodiment, semiconductor layer **141** has a dopant concentration from about 1.5×10^{15} atoms/cm^3 to about 2.5×10^{15} atoms/cm^3. It was found that these doping levels are sufficiently low so as to not impact the channel properties of device **10**. In one embodiment, semiconductor layer **141** has a thickness of about 10 microns and can be formed using techniques such as epitaxial growth techniques, which forms an as-doped region. In an alternative embodiment, semiconductor layer **141** can be formed by ion implanting (for example, a p-type implant) after a portion of semiconductor layer **14** is formed and before growing the remaining portion of semiconductor layer **14**. Such an implant can be performed using, for example, blanket implant conditions, through one of the existing mask layers (for example, the mask layer used to form body region **31** described later) or with a dedicated mask. As in the epitaxial growth approach in forming semiconductor layer **141**, the blanket implant can place semiconductor layer **141** in the termination region and can support the implementation of predetermined termination structures. Using a mask to reduce the presence of semiconductor layer **141** in the termination region of device **10** makes the present embodiment further compatible with other existing termination designs, which is helpful for cost effective integration. A dedicated mask defining a certain distance from semiconductor layer **141** to the N-pillar (i.e., layer **221** described below) can be used to effectively reduce the Rdson impact in the present embodiment.

Device **10** further includes spaced apart filled trenches, compensating trenches, semiconductor material filled

trenches, charge-compensated trench regions, LCB regions, LCB structures, charge-compensated filled trenches, compensation trenches, localized vertical charge compensation structures, or LCB regions or pillars **22**. As used herein, charge compensation generally means that the total charge of the opposite conductivity type layers is substantially or generally balanced or equal. Charge-compensated filled trenches **22** include a plurality of layers or multiple pillars of material, conductive material or semiconductor material **220**, including at least two layers or pillars of opposite conductivity type (i.e., at least one each of n-type and p-type), which may be separated by an intrinsic, buffer, or lightly doped semiconductor layer or layers. As shown in FIG. **1**, material **220** includes a pillar or layer **221** of n-type semiconductor material adjoining semiconductor layer **14** and semiconductor layer **141** along sidewall surfaces of trenches **22**.

In accordance with a one embodiment, layers **221** are of the same conductivity type as source regions **33**, and form a primary vertical low resistance current path from the channel to the drain when device **10** is in the on-state. A layer **222** of compensating p-type semiconductor material is formed overlying or overlies layer **221**. By way of example, n-type layers **221** and p-type layers **222** have a dopant concentration on the order of about 1.0×10^{15} to about 1.0×10^{17} atoms/cm^3, and each has a thickness of about 0.1 microns to about 0.4 microns. Depending on the desired charge balance, the foregoing dopant concentrations are increased or decreased accordingly. When device **10** is an off state, p-type layers **222** and n-type layers **221** compensate each other to provide an increased BVdss characteristic. Although no buffer layers are shown in the device of FIG. **1**, it is understood that they may be present in earlier steps in fabrication and may not be as evident because dopant can diffuse into such layers during subsequent high temperature processing. In one embodiment, layers of semiconductor material **220** comprise a single crystalline semiconductor material and have as-formed dopant profiles.

In one embodiment, device **10** also includes one or more dielectric layers, dielectric structure, or dielectric plug **28** formed overlying pillars **220** within trenches **22**. In one embodiment, dielectric layer **28** is a deposited silicon oxide layer. It is understood that dielectric layer **28** can be more than one dielectric layer and can be different materials. Although not shown, it is understood that during the formation of device **10**, n-type dopant from highly doped substrate **12** can diffuse into the lower portions of charge-compensated trenches **22** so that those portions of trenches **22** within substrate **12** become more heavily doped n-type.

Device **10** also includes a well, base, body or doped regions **31** formed in semiconductor layer **141** between and in proximity to, adjacent to, or adjoining charge-compensated trenches **22**. Body regions **31** extend from major surface **18** of semiconductor material **11**. In one embodiment, body regions **31** comprise p-type conductivity, and have a dopant concentration suitable for forming an inversion layer that operates as conduction channels **45** of device **10**. Body regions **31** extend from major surface **18** to a depth of about 1.0 to about 5.0 microns. As stated above, body regions **31** can be a plurality of individually diffused regions or can be a connected, single or commonly diffused region of selected shape, or combinations thereof.

N-type source regions **33** are formed within, above, or in body regions **31** and extend from major surface **18** to a depth of about 0.2 microns to about 0.5 microns. In the embodiment shown, portions of major surface **18** extend down and then outward from the edges of source regions **33** so that contact is made to horizontal and vertical surfaces of source regions **33** by source contact layer **63**. One or more p-type body contact regions **36** are formed in at least a portion of each body region **31**. Body contact regions **36** are configured to provide a lower contact resistance to body region **31**, and to lower the sheet resistance of body regions **31** under source regions **33**, which suppresses parasitic bipolar effects.

Device **10** further includes a trench gate or control structure **157** adjoining body regions **31** and source regions **33**. Control structure **157** is laterally spaced apart from adjacent charge-compensated trenches **22**. That is, control structure **157** does not overlie charge-compensated trenches **22**. Trench gate structure **157** includes a gate trench **158** and a gate dielectric layer **43** formed overlying surfaces of gate trench **158**. In one embodiment, gate dielectric layer **43** comprises a silicon oxide, and has a thickness of about 0.05 microns to about 0.1 microns. In another embodiment, gate dielectric layer **43** has a thickness at the lower surfaces of gate trench **158** that is greater or thicker than the thickness of gate dielectric layer **43** along the sidewalls of gate trench **158**. In alternative embodiments, gate dielectric layer **43** comprises silicon nitride, tantalum pentoxide, titanium dioxide, barium strontium titanate, or combinations thereof including combinations with silicon oxide, or the like.

Trench gate structure **157** further includes a conductive gate region **57** formed within control or gate trench **158** and overlies gate dielectric layer **43**. In one embodiment, a source region **33** is interposed between a conductive gate region **57** and a charge compensation trench **22**. Conductive gate region **57** comprises, for example, n-type polysilicon. Although conductive gate region **57** is shown as recessed below major surface **18**, conductive gate region **57** may extend higher or above major surface **18**. Trench gate structure **157** is configured to control the formation of channels **45** and the conduction of current in device **10**.

To facilitate a sub-surface current path, device **10** further includes n-type link, n-type doped doped layers or sub-surface doped layers **26**. Specifically, doped layers **26** are configured to provide a sub-surface conduction path between the drain end of channels **45** and n-type layers **221**, which are the primary conduction layers or vertical conduction paths in charge compensation trenches **22**. That is, in device **10** current flows vertically through channels **45**, then horizontally through doped layers **26**, and then vertically through layers **221**. Doped layers **26** are configured so that current flow is isolated from major surface **18** by body regions **31** and body contact regions **36**, which are opposite conductivity types (p-type) from doped layers **26** (n-type). This isolation feature keeps the conduction path away from defect regions near the surface thereby avoiding any conduction related problems.

Device **10** further includes an interlayer dielectric region **48** formed on or above major surface **18**, which is patterned to provide openings to body contact regions **36** and source regions **33**. A portion of interlayer dielectric region **48** is left overlying trench gate structure **157** to provide isolation for conductive gate region **57**. Interlayer dielectric region **48** comprises for example, a silicon oxide such as a deposited oxide, and has a thickness from about 0.4 microns to about 1.0 microns. It is understood that contact can be made to conductive gate region **57** on another portion of device **10** (not shown).

Source contact layer **63** is formed on or above major surface **18** and makes contact to both source regions **33** and body contact regions **36**. In one embodiment, source contact layer **63** comprises a titanium/titanium nitride barrier layer and an aluminum silicon alloy formed overlying the barrier layer, or the like. Drain contact layer **13** is formed overlying an opposing surface of semiconductor material **11**, and comprises, for

example, a solderable metal structure such as titanium-nickel-silver, chrome-nickel-gold, or the like. Device **10** is further illustrated with an optional n-type buffer layer **143**, which will be described in another embodiment subsequently.

The operation of device **10** proceeds as follows. Assume that source terminal **63** is operating at a potential V_S of zero volts, conductive gate regions **157** receive a control voltage V_G=5.0 volts, which is greater than the conduction threshold of device **10**, and drain terminal **13** operates at drain potential V_D=5.0 volts. The values of V_G and V_S cause body region **31** to invert adjacent conductive gate regions **157** to form vertical channels **45**, which electrically connect source regions **33** to doped regions **26**. A device current Id flows from drain terminal **13** and is routed through n-type pillars **221**, doped layer **26**, channels **45**, source regions **33**, to source terminal **63**. Hence, current Id flows vertically through n-type pillars **221** to produce a low on-resistance, and horizontally through n-type links **26** keeping the current path isolated from major surface **18**. In one embodiment, Id=1.0 amperes. To switch device **10** to the off state, a control voltage V_G of less than the conduction threshold of the device is applied to conductive gate regions **157** (e.g., V_G<5.0 volts). This removes channels **45** and Id no longer flows through device **10**. In the off state, n-type pillars **221** and p-type pillars **222** compensate each other as the depletion region from the primary blocking junction spreads, which enhances BVdss.

The benefits of p-type semiconductor layer **141** in the present embodiment are further illustrated in FIGS. **2** and **3**. FIG. **2** illustrates BVdss (V) as a function of charge balance percentage (CB %) where curve **201** represents a prior device without an n-type buffer below the n-type drift region, curve **202** represents a prior structure with an n-type buffer below the n-type drift region, and curve **203** represent the present embodiment with p-type semiconductor layer **141** without an n-type buffer layer below the n-type drift region. FIG. **3** illustrates Isnapback (A) as a function of charge balance percentage (CB %) where curve **301** represents a prior device without an n-type buffer, curve **302** represents a prior structure with an n-type buffer, and curve **303** represent the present embodiment with p-type semiconductor layer **141**. This data illustrates, for example, that in the present embodiment the Isnapback U-shape is reduced, and Isnapback is shifted above about 50 amps (A) including for a charge balanced structure (i.e., CB=0%).

FIG. **4** illustrates graphical information of drain current (Id) vs. breakdown voltage (BVdss) comparing device **10** (curve **401**) with a CB of 5% to a prior structure (curve **402**) that does not include p-type semiconductor layer **141**. As illustrated in FIG. **4**, device **10** exhibits improved Isnapback performance.

FIG. **5** illustrates graphical information of example Id-Vd curves for device **10** of the present embodiment generated using simulations under isothermal conditions. Curve **501** corresponds to a CB of −5%; curve **502** corresponds to a CB of −2.5%; curve **503** corresponds to a CB of 10%; curve **504** corresponds to a CB of 7.5%; curve **505** corresponds to a CB of 0%; curve **506** corresponds to a CB of 2.5%; and curve **507** corresponds to a CB of 5%. An explanation of the physical mechanisms for the higher Isnapback in accordance with the present embodiment is provided subsequently. In the present embodiment, the BVdss is believed to be enhanced due to a more optimum electric field distribution towards the top or upper surface of device **10** that adds ruggedness during avalanche cycling tests. In accordance with the present embodiment, avalanche occurs deeper into the semiconductor material because of the presence of semiconductor layer **141**. Thus, the degradation after multiple UIS cycles (or other tests that induce avalanche) is less compared to previous structures where the avalanche takes place close to the interface between p-type pillars **222** and dielectric plug **28**. It was also observed in the present embodiment that the impact ionization distribution tends to follow the electric field distribution.

In the present embodiment, the targeted Rdson can be dependent upon the characteristics of semiconductor layer **141** and the fabrication method used to form this region of device **10**. In one embodiment, an Rdson degradation ranging from 5% to 20% was found in simulated structures. However, the present embodiment was found to be a more robust device compared to a device with only an n-type buffer for a similar Rdson. There are believed to be at least two elements that may impact Rdson in the present embodiment. With a minor impact, semiconductor layer **141** may block the current conduction through the lighter doped semiconductor layer **14**. Because most of the current flows through n-type pillars **221**, this may be less of a concern for LCB devices (but it would be more of a concern for GCB or planar devices). Additionally, the enhanced JFET effect at the n-type link **26** and n-type pillar **221** region can have a greater impact for Rdson measured at a high drain voltage. In other embodiments, these results can be improved by optimizing (for example, dopant levels or dopant profiles) the n-type link **26** and n-type pillar **221** structures.

It was observed that at a drain current (Id) of 10 amps, the electric field decrement at semiconductor layer **14** can be compensated by the electric field increment at semiconductor layer **141**, thus generating a positive differential resistance. In the baseline structure with the non-optimized n-type buffer layer, the negative differential resistance occurs for I<10 A due to a reduction of electric field in the drift region. The presence of semiconductor layer **141** enables Isnapback>50 A for the complete CB range as illustrated in FIG. **5**; however when semiconductor layer **141** is combined with the addition of an n-type buffer (represented by layer **143** in FIG. **1**), Isnapback can be even larger and the electric field can be extended to the n-type buffer layer for I>100 A.

The present embodiment can be implemented by different manufacturing methods. As described previously, in one embodiment the last portion (for example, about 10 microns) of semiconductor layer **14** is replaced by semiconductor layer **141** doped with boron. In one embodiment, the presence of semiconductor layer **141** provides an improvement after analyzing the BVdss and Isnapback dependencies with the thickness of semiconductor layer **141** (Tpepi) and the dopant concentration (Pepi) thereof as illustrated respectively in FIGS. **6** and **7**. Curves **601** and **701** represent breakdown voltage in FIGS. **6** and **7** respectively, and curves **602** and **702** represent Isnapback respectively. It was observed, for example, that if Tpepi and Pepi are too low then an Isnapback reduction of orders of magnitude can result. If Tpepi and Pepi are too high a degradation of BVdss can occur.

An alternative method to implement the present embodiment is to perform an ion implantation (for example, p-type implantation when device **10** is an n-channel device) before growing the final portion of semiconductor layer **14**. FIG. **8** illustrates that the ion implantation method provides similar results to the epitaxial growth method. Curves **801** and **802** represent breakdown voltage and snapback current respectively for a p-type implant done before growing a final 10 microns of n-type semiconductor layer **14**; and curves **803** and **804** represent breakdown voltage and snapback current respectively before growing the final 6 microns of n-type semiconductor layer **14**.

Further studies of device **10** showed that incorporating semiconductor layer **141** resulted in only a minor impact on electrical performance compared to a previous structure without such a layer in Rdson performance. However, total gate charge (Qg) and capacitances were not degraded in device **10**. Also, device **10** was found to exhibit similar efficiency compared to the previous structure in a typical boost converter application, which was further verified by mixed-mode simulations.

In one embodiment, due to the low doping concentration of semiconductor layer **141**, the activation of the parasitic bipolar transistor formed between n-type link **26**, p-type semiconductor layer **141**, and n-type semiconductor layer **14** (Nlink-Pepi-Nepi) can be reduced or avoided. A variation of the present embodiment includes electrically connecting semiconductor layer **141** to source contact layer **63** on another portion of device **10**, which is generally illustrated in FIG. **9** and further illustrated by the dashed connective line between the Vs terminal in FIG. **1** and semiconductor layer **141**. In this configuration, it was observed that the BVdss is similar (about 15 volts less for the source connected to semiconductor layer **141** embodiment) while Isnapback increased due to the grounded bipolar base region (i.e., semiconductor layer **141**) by about 2×. This embodiment was simulated in a boost converter (for example, 90V to 400V) by mixed-mode simulations and showed similar efficiency compared previous structures that did not have semiconductor layer **141** in accordance with (for example, same turn-off and turn-on times).

In view of all of the above, it is evident that a novel structure and method are disclosed. Included, among other features, is forming a low-doped p-type region adjoining a vertical superjunction structure. In one embodiment, the low-doped p-type region is formed below an n-type linking and above a low doped n-type region. The low-doped p-type region is configured, among other things, to improve Eas performance without significantly impacting other performance parameters. In another embodiment, the conductivity types can be reversed.

While the subject matter of the invention is described with specific preferred embodiments and example embodiments, the foregoing drawings and descriptions thereof depict only typical embodiments of the subject matter, and are not therefore to be considered limiting of its scope. It is evident that many alternatives and variations will be apparent to those skilled in the art.

As the claims hereinafter reflect, inventive aspects may lie in less than all features of a single foregoing disclosed embodiment. Thus, the hereinafter expressed claims are hereby expressly incorporated into this Detailed Description of the Drawings, with each claim standing on its own as a separate embodiment of the invention. Furthermore, while some embodiments described herein include some but not other features included in other embodiments, combinations of features of different embodiments are meant to be within the scope of the invention and meant to form different embodiments as would be understood by those skilled in the art.

We claim:

1. A semiconductor device comprising:

a semiconductor substrate defining a major surface;

a first region comprising at least a first pillar of a first conductivity type, and a second pillar of a second conductivity type extending in a generally vertical orientation with respect to the major surface, wherein the first conductivity type is opposite to the second conductivity type, and wherein the first pillar is configured as a vertical current path;

a second region of the first conductivity type spaced apart from the major surface and adjoining a lower portion of the first region;

a third region of the second conductivity type adjoining the first region between the major surface and the second region;

a body region of the second conductivity type between a portion of the third region and the major surface;

a source region of the first conductivity type adjoining the body region; and

a control electrode adjoining the body region and the source region and configured to control a channel region within the body region but not within the third region.

2. The device of claim **1** further comprising a fourth region of the first conductivity type between the body region and the third region and configured to link a drain end of the channel region to the first region.

3. The device of claim **1**, wherein the third region has a dopant concentration in a range from about 1.0×10^{15} atoms/cm^3 to about 4.0×10^{15} atoms/cm^3, and wherein the first region has a charge balance other than zero.

4. The device of claim **1**, wherein the third region has a dopant concentration in a range from about 1.0×10^{15} atoms/cm^3 to about 3.0×10^{15} atoms/cm^3.

5. The device of claim **1**, wherein the first pillar of the first conductivity type adjoins the second and third regions.

6. The device of claim **1**, wherein the control electrode comprises a trench control electrode, and wherein the third region overlaps the trench control electrode and the trench control electrode terminates within the third region.

7. The device of claim **1** further comprising a conductive layer electrically connected to the source region and the third region.

8. A semiconductor device comprising:

a substrate;

a semiconductor layer overlying the substrate, wherein the semiconductor layer has a major surface spaced apart from the substrate;

a vertically-oriented charge balance region adjacent to the major surface and extending towards the substrate;

a body region of a first conductivity type adjacent to another portion of the major surface;

a first horizontally-oriented doped region of a second conductivity type spaced apart from the major surface and between the body region and the substrate, wherein the first horizontally-oriented doped region adjoins the vertically-oriented charge balance region;

a second horizontally-oriented doped region of the first conductivity type spaced apart from the major surface and between the first horizontally-oriented doped region and the substrate; and

a gate electrode electrically insulated from the body region and the first horizontally-oriented doped region,

wherein:

a transistor structure of the semiconductor device comprises the first horizontally-oriented doped region, the body region, and the gate electrode;

the second horizontally-oriented doped region is configured to shift avalanche regions away from the gate electrode and from upper portions of the vertically-oriented charge balance structure towards the semiconductor layer; and

the vertically-oriented charge balance structure electrically connects the transistor structure and the substrate to each other.

9. The structure of claim 8, wherein the second horizontally-oriented doped region has a dopant concentration in range from about 1.0×10^{15} atoms/cm^3 to about 4.0×10^{15} atoms/cm^3.

10. The structure of claim 8, wherein the second horizontally-oriented doped region has a dopant concentration between about 1.0×10^{15} atoms/cm^3 to about 3.0×10^{15} atoms/cm^3.

11. The structure of claim 8, wherein the second horizontally-oriented doped region has a thickness from about five microns to about fifteen microns.

12. The structure of claim 8, wherein the gate electrode comprises a trench gate electrode, and wherein the second horizontally-oriented doped region overlaps the gate electrode and the gate electrode terminates within the second horizontally-oriented doped region.

13. The structure of claim 8, wherein the vertically-oriented charge balance region comprises a plurality of first conductivity type and second conductivity type pillars.

14. The structure of claim 8 further comprising a source region formed in the body region and a conductive layer electrically connected to the source region and the second horizontally-oriented doped region.

15. A semiconductor device comprising:

a semiconductor substrate defining a major surface;

a first region comprising at least a first pillar of a first conductivity type, wherein the first pillar is configured as a vertical current path;

a body region of a second conductivity type opposite to the first conductivity type adjacent the major surface;

a source region of the first conductivity type adjoining the body region;

a second region of the first conductivity type spaced apart from the major surface and adjoining a lower portion of the first region;

a third region of the second conductivity type adjoining the first region between the major surface and the second region;

a control electrode adjoining the body region and the source region and configured to control a channel region within the body region but not within the third region; and

a fourth region of the first conductivity type between the body region and the third region and configured to provide a generally horizontal current path between a drain end of the channel region and the first region.

16. The device of claim 15, wherein:

the first region further comprises a second pillar of a second conductivity type extending in a generally vertical orientation with respect to the major surface; and

the third region is configured to enhance electrical field distribution during an avalanche condition.

17. The device of claim 16, wherein the first region has a charge balance greater than zero percent and less than about ten percent, and wherein the third region has a thickness in range from about five microns to about fifteen microns.

18. The device of claim 16, wherein the first region has charge balance greater than negative five percent and less than zero percent.

19. The device of claim 15 further comprising a conductive layer electrically connected to the source region and the third region.

20. The device of claim 15, wherein the control electrode comprises a trench control electrode extending into the semiconductor substrate, and wherein the third region overlaps the control electrode such that the control electrode terminates within the third region, and wherein the device further comprises a buffer layer, wherein the second region is between the buffer layer and the third region.

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